

1. RESONANCES

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1.1. General Considerations

For simplicity, throughout this review the formulas are given for distinguishable, scalar particles. The additional complications that appear in the presence of spins can be controlled in the helicity framework developed by Jacob and Wick [1], or in a non-relativistic [2] or relativistic [3] tensor operator formalism. Within these frames, sequential (cascade) decays are commonly treated as a coherent sum of two-body interactions. Therefore below most concrete expressions are given for two-body kinematics.

1.1.1. Properties of the S -matrix:

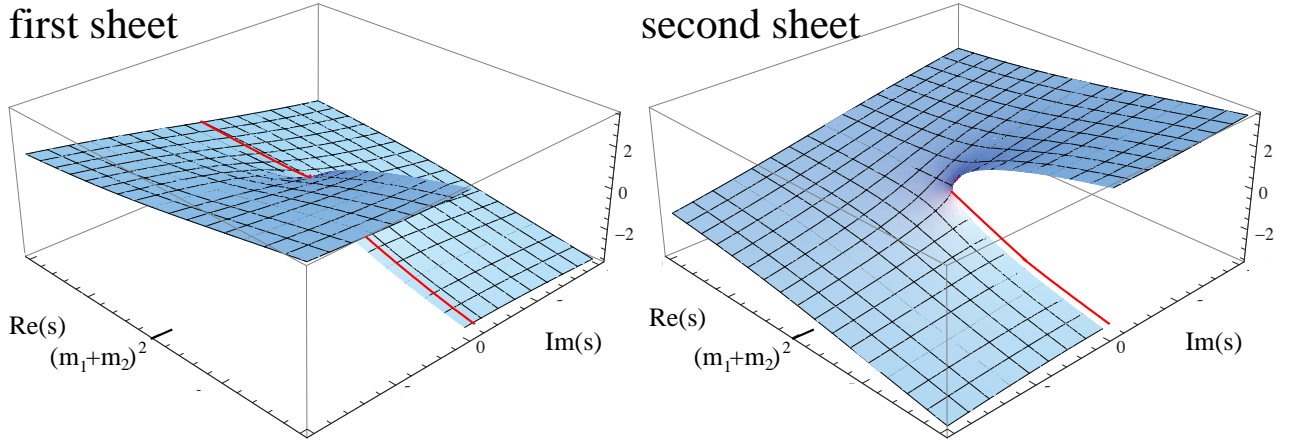


Figure 1.1: Sketch of the imaginary part of a typical single-channel amplitude in the complex s -plane. The solid dots indicate allowed positions for resonance poles, the cross for a bound state. The solid line is the physical axis (shifted by $i\epsilon$ into the first sheet). The two sheets are connected smoothly along their discontinuities.

The unitary operator that connects asymptotic *in* and *out* states is called the S -matrix. It is an analytic function in the Mandelstam plane up to its branch points and poles. Branch points appear whenever there is a channel opening — at each threshold the number of Riemann sheets doubles. Poles refer either to bound states or to resonances. The former poles are located on the physical sheet, the latter are located on the unphysical sheet closest to the physical one, traditionally called the second sheet; each can be accompanied by mirror poles. If there are resonances in subsystems of multi-particle final states, branch points appear in the complex plane of the second sheet. Any of these singularities leads to some structure in the observables (see also Ref. [4]). In a partial wave decomposed amplitude additional singularities may emerge as a function of the partial-wave projection. For a discussion see, e.g., Ref. [6].

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If for simplicity we now restrict ourselves to reactions involving four particles, the kinematics of the reaction are fully described by the Mandelstam variables s , t and u (cf. Eqs. (28)-(30) of the kinematics review). Bound state poles are allowed only on the real s -axis below the lowest threshold. There is no restriction for the location of poles on the second sheet — only that analyticity requires that, if there is a pole at some complex value of s , there must also be a pole at s^* . The pole with a negative imaginary part is closer to the physical axis and thus influences the observables in the vicinity of the resonance region more strongly, however, at the threshold both poles are always equally important. This is illustrated in Fig. 1.1.

The S -matrix is related to the scattering matrix \mathcal{M} (c.f. Eq. (8) of the kinematics review). For two-body scattering it can be cast into the form

$$S_{ab} = I_{ab} - 2i\sqrt{\rho_a}\mathcal{M}_{ab}\sqrt{\rho_b}. \quad (1.1)$$

\mathcal{M} is a matrix in channel space and depends, for two-body scattering, on both s and t . The channel indices a and b are multi-indices specifying all properties of the channel including the conserved quantum numbers. The two-body phase-space ρ is given (cf. Eq. 12 of the kinematics review) by

$$\rho_a(s) = \frac{1}{16\pi} \frac{2|\vec{q}_a|}{\sqrt{s}}. \quad (1.2)$$

with q_a denoting the relative momentum of the decay particles of channel a , with masses m_1 and m_2 , cf. Eq. (20a) of the kinematics review.

1.1.2. Consequences from unitarity:

In what follows, scattering amplitudes \mathcal{M} and decay amplitudes \mathcal{A} will be distinguished, since unitarity puts different constraints on these. The discontinuity of the scattering amplitude from channel a to channel b [7] is constrained by unitarity to

$$i[\mathcal{M}_{ba} - \mathcal{M}_{ab}^*] = (2\pi)^4 \sum_c \int d\Phi_c \mathcal{M}_{cb}^* \mathcal{M}_{ca}. \quad (1.3)$$

Using $\text{Disc}(\mathcal{M}(s)) = 2i \text{Im}(\mathcal{M}(s + i\epsilon))$ the optical theorem follows

$$\text{Im}(\mathcal{M}_{aa}|_{\text{forward}}) = 2q_a \sqrt{s} \sigma_{\text{tot}}(a \rightarrow \text{anything}). \quad (1.4)$$

The unitarity relation for a decay amplitude of a heavy state H into a channel a is given by

$$i[\mathcal{A}_a^H - \mathcal{A}_a^{H*}] = (2\pi)^4 \sum_c \int d\Phi_c \mathcal{M}_{ca}^* \mathcal{A}_c^H. \quad (1.5)$$

From Eq. (1.5) the Watson theorem follows straightforwardly: the phase of \mathcal{A} agrees to that of \mathcal{M} as long as only a single channel contributes. For systems where the phase shifts are known like $\pi\pi$ in S - and P -waves for low energies, the vector \mathcal{A}^H can be calculated in a model independent way using dispersion theory [8]. Those methods can also be generalized to three-body final states and were applied to $\eta \rightarrow \pi\pi\pi$ in Ref. [9,10,11] and to ϕ and ω to 3π in Ref. [12].

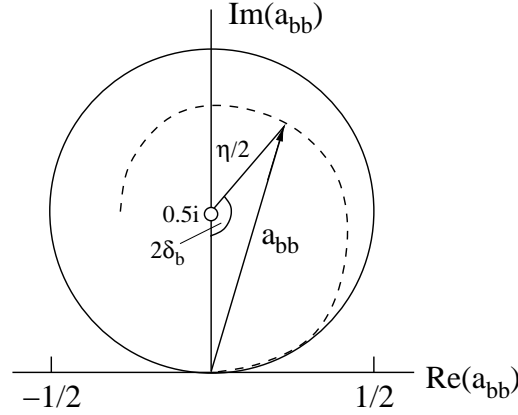


Figure 1.2: Argand plot showing a diagonal element of a partial-wave amplitude, a_{bb} , as a function of energy. The amplitude leaves the unitary circle (solid line) as soon as inelasticity sets in, $\eta < 1$ (dashed line).

1.1.3. Partial-wave decomposition:

In general, a physical amplitude \mathcal{M} (c.f. Eq. (8) of the kinematics review) is a matrix in channel space. It depends, for two-body scattering, on both s and t . It is often convenient to expand the amplitudes in partial waves. For this purpose one defines for the transition matrix from channel a to channel b

$$\mathcal{M}_{ba}(s, t) = \sum_{L=0}^{\infty} (2L+1) \mathcal{M}_{ba}^L(s) P_L(\cos(\theta)) , \quad (1.6)$$

where L denotes the angular momentum—in the presence of spins the initial and final value of L does not to be equal. To simplify notations below we will drop the label L . The function $\mathcal{M}_{ba}(s)$ is expressed in terms of the partial-wave amplitudes $a_{ba}(s)$ via

$$\mathcal{M}_{ba}(s) = -a(s)_{ba} / \sqrt{\rho_a \rho_b} . \quad (1.7)$$

The partial-wave amplitudes a_{ba} depend on s only. Using $S_{ba} = \delta_{ba} + 2ia_{ba}$ one gets from the unitarity of the S -matrix

$$a_{bb} = (\eta \exp(2i\delta_b) - 1) / 2i , \quad (1.8)$$

where δ_b (η) denote the phase shift (inelasticity) for the scattering from channel b to channel b . One has $0 \leq \eta \leq 1$, where $\eta = 1$ refers to purely elastic scattering. The evolution with energy of a partial-wave amplitude a_{bb} can be displayed as a trajectory in an Argand plot, as shown in Fig. 1.2. In case of a two-channel problem the off-diagonal element is typically parametrized as $a_{ba} = \sqrt{1 - \eta^2/2} \exp(i(\delta_b + \delta_a))$.

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1.1.4. Concrete parametrizations for scattering and production amplitudes:

It is often convenient to decompose the physical amplitude \mathcal{M} into a pole part and a non-pole part, often called background

$$\mathcal{M} = \mathcal{M}^{\text{b.g.}} + \mathcal{M}^{\text{pole}} . \quad (1.9)$$

The splitting given in Eq. (1.9) is not unique and reaction dependent, such that some resonances show up differently in different reactions. What is independent of the reaction, however, are the locations of the poles as well as their residues. Those parameters capture all the properties of a given resonance. The decomposition of Eq. (1.9) is employed, e.g., in Ref. [13] to study the lineshape of $\psi(3770)$ and in Refs. [14,15] to investigate πN scattering.

If there are N resonances in a particular channel,

$$\mathcal{M}_{ba}^{\text{pole}}(s) = \gamma_b(s) \left[1 - V^{\text{R}}(s) \Sigma(s) \right]_{bc}^{-1} V_{ca}^{\text{R}}(s) \gamma_a(s) . \quad (1.10)$$

where all ingredients are matrices in channel space. Especially

$$V_{ab}^{\text{R}}(s) = - \sum_{n=1}^N \frac{g_{nb} g_{na}}{s - M_n^2} , \quad (1.11)$$

γ_a and Σ_a denote the normalized vertex function and the self energy, g_{na} denotes the coupling of the resonance R_n to channel a and M_n its mass parameter (not to be confused with the pole position). A relation analogous to Eq. (1.5) holds for any kind of production amplitude — especially also for the normalized vertex functions, however, with the final state interaction provided by $\mathcal{M}^{\text{b.g.}}$.

$$i[\gamma_a - \gamma_a^*] = (2\pi)^4 \sum_c d\Phi_c \left(\mathcal{M}^{\text{b.g.}} \right)_{ca}^* \gamma_c . \quad (1.12)$$

The discontinuity of the self energy $\Sigma_a(s)$ is

$$i[\Sigma_a - \Sigma_a^*] = (2\pi)^4 \int d\Phi_a |\gamma_a|^2 . \quad (1.13)$$

The real part of Σ_a can be calculated from Eq. (1.13) via a properly subtracted dispersion integral. If $\mathcal{M}^{\text{b.g.}}$ is unitary, the use of Eq. (1.10) leads to a unitary full amplitude, cf. Eq. (1.9).

If there are no prominent left-hand cuts in the production mechanism, the decay amplitude \mathcal{A}^H can be written as

$$\mathcal{A}_a^H(s) = \gamma_a(s) \left[1 - V^{\text{R}}(s) \Sigma(s) \right]_{ab}^{-1} \mathcal{P}_b^H(s) , \quad (1.14)$$

where \mathcal{P}^H is a vector in channel space that may be parametrized as

$$\mathcal{P}_b^H(s) = p_b(s) - \sum_{n=1}^N \frac{g_{nb} \alpha_n^H}{s - M_n^2} \quad (1.15)$$

and the masses M_n need to agree with those in V_R . The function $p_a(s)$ is a background term and the α_n^H denote the coupling of the heavy state H to the particular resonance R_n (and eventually to additional particles for which the final state interaction is neglected). With some additional assumptions, Eq. (1.9) and Eq. (1.14) were employed in Ref. [16] to study the pion vector form factor. An alternative parametrization for the production amplitude that is convenient, if the full matrix \mathcal{M} — including the resonances — is known, is given in Ref. [17]

$$\mathcal{A}_a^H(s) = \mathcal{M}_{ab}(s) \tilde{\mathcal{P}}_b^H(s) .$$

The function $\tilde{\mathcal{P}}_H(s)_b$ needs to cancel the left-hand cuts of \mathcal{M} and therefore could be strongly energy dependent. In actual applications a low-order polynomial turned out to be sufficient — c.f. Ref. [17] for a study of $\gamma\gamma \rightarrow \pi\pi$.

For a single resonance ($N = 1$) Eq. (1.10) reads

$$\mathcal{M}_{\text{pole}}(s)_{ba}|_{N=1} = -\gamma_b(s) \frac{g_b g_a}{s - \hat{M}_R(s)^2 + i\sqrt{s}\Gamma^R(s)_{\text{tot}}} \gamma_a(s) , \quad (1.16)$$

where the mass function $\hat{M}_R(s)^2 = M^2 + \sum_c g_c^2 \text{Re}(\Sigma_c)$. The imaginary part of the self energy gives the width of the resonance via

$$\Gamma_c^R(s) = \frac{(2\pi)^4}{2\sqrt{s}} g_c^2 \int d\Phi_c |\gamma_c|^2; \quad \Gamma^R(s)_{\text{tot}} = \sum_c \Gamma_c^R(s) . \quad (1.17)$$

Here the sum runs over all channels. Eq. (1.17) agrees with Eq. (10) of the kinematics review.

The formulas given so far are completely general, however, they require as input, e.g., information on the non-resonant scattering in the various channels. It is therefore often necessary and appropriate to find approximations/parametrizations.

1.2. Common parametrizations for resonances

In most common parametrizations the non-pole interaction, $\mathcal{M}^{\text{b.g.}}$, is omitted. While this is a bad approximation for, e.g., scalar-isoscalar $\pi\pi$ interactions at very low energies, under more favorable conditions this can be justified. Thus in what follows we will assume $\mathcal{M}^{\text{b.g.}} = 0$, which leads to real vertex functions. For two-body channels one writes

$$\gamma(s)_a = q_a^{L_a} F_{L_a}(q_a, q_0) ,$$

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where L_a denotes the angular momentum of the decay products, giving rise to the centrifugal barrier $q_a^{L_a}$. Often one introduces a phenomenological form factor, here denoted by $F_{L_a}(q_a, q_o)$. It depends on the channel momentum as well as some intrinsic scale q_o . Often the Blatt-Weisskopf form is chosen [18,19], where, e.g., $F_0^2 = 1$, $F_1^2 = 2/(q_a + q_o)$ and $F_2^2 = 13/((q_a - 3q_o)^2 + 9q_a q_o)$. In addition, the couplings g_a can be related to the partial widths via

$$g_a = \frac{1}{\gamma_a(s_R)} \sqrt{\frac{M_R \Gamma_a^R (M_R^2)}{\rho_a}}, \quad (1.18)$$

where $M_R = \text{Re}(\sqrt{s_R})$ denotes the mass of the resonance located at $s = s_R$.

1.2.1. The Breit-Wigner and Flatté Parametrizations:

If there is only a single resonance present and all relevant thresholds are far away, then one may replace $\Gamma_R(s)_{\text{tot}}$ with a constant, Γ_0 . Under these conditions also the real part of Σ is a constant that can be absorbed into the parameter M_R and Eq. (1.16) simplifies to

$$\mathcal{M}_{ba}^{\text{pole}} \Big|_{N=1} = -\frac{g_b g_a}{s - M_R^2 + i\sqrt{s}\Gamma_0}, \quad (1.19)$$

which is the standard Breit-Wigner parametrization. For a narrow resonance it is common to replace \sqrt{s} by M_R . If there are nearby relevant thresholds, Γ_0 becomes s dependent. For two-body decays one writes

$$\Gamma(s) = \sum_c \Gamma_c \left(\frac{q_c}{q_{Rc}} \right)^{2L_c+1} \left(\frac{F_{L_c}(q_c, q_o)}{F_{L_c}(q_{Rc}, q_o)} \right)^2, \quad (1.20)$$

where $q_{Rc} = q(M_R)_c$ denotes the decay momentum of resonance R into channel c . Traditionally M_R and $\Gamma(M_R)$ are quoted as Breit-Wigner parameters. However, those agree to the pole parameters only if $M_R \Gamma(M_R) \ll M_{\text{thr}}^2 - M_R^2$, with M_{thr} for the closest relevant threshold. Otherwise the Breit-Wigner parameters deviate from the pole parameters and are reaction dependent.

If there is more than one resonance in one partial wave that significantly couples to the same channels, it is in general incorrect to use a sum of Breit-Wigner functions, for it may violate unitarity constraints. Then more refined methods should be used, like the K -matrix approximation described in the next section.

Below the corresponding threshold, q_c in Eq. (1.20) must be continued analytically: if, e.g., the particles in channel c have equal mass m_c , then

$$q_c = \frac{i}{2} \sqrt{4m_c^2 - s} \quad \text{for} \quad \sqrt{s} < 2m_c. \quad (1.21)$$

The resulting line shape above and below the threshold of channel c is called Flatté parametrization [20]. If the coupling of a resonance to the channel opening nearby is very strong, the Flatté parametrization shows a scaling invariance and does not allow for an extraction of individual partial decay widths, but only of ratios [21].

1.2.2. The K -matrix approximation:

As soon as there is more than one resonance in one channel, the use of the K -matrix approximation should be preferred compared to the Breit-Wigner parametrization discussed above. From the considerations formulated in Eq. (1.10), the K -matrix approximation follows straightforwardly by replacing the self energy Σ_c by its imaginary part in the absence of $\mathcal{M}^{\text{b.g.}}$, but keeping the full matrix structure of V^{R} . Thus, for two-body intermediate states one writes within this scheme for the self energy

$$\Sigma(s)_c \rightarrow i\rho_c \gamma(s)_c^2 . \quad (1.22)$$

However, in distinction to the Breit-Wigner approach, V^{R} , then called K -matrix, is kept in the form of Eq. (1.11). The decay amplitude given in Eq. (1.14) then takes the form of the standard P -vector formalism introduced in Ref. [22]. For $N = 1$ the amplitude derived from the K -matrix is identical to that of Eq. (1.19).

Some authors use the analytic continuation of ρ_c below the threshold via the analytic continuation of the particle momentum as described above [23].

1.2.3. Further improvements:

The K -matrix described above usually allows one to get a proper fit of physical amplitudes and it is easy to deal with, however, it also has an important deficit: it violates constraints from analyticity — e.g., ρ_a , defined in Eq. (1.2), has a pole at $s = 0$ and for unequal masses develops an unphysical cut. In addition, the analytic continuation of the amplitudes into the complex plane is not controlled and typically the parameters of broad resonances come out wrong (see, e.g., minireview on scalar mesons). A method to improve the analytic properties was suggested in Refs. [24,25,26,27]. It basically amounts to replacing the phase-space factor $i\rho_a$ in Eq. (1.22) by an analytic function that produces the identical imaginary part on the right hand cut. In the simplest case of a channel with equal masses the expressions that can be used for real values of s read

$$-\frac{\hat{\rho}_a}{\pi} \log \left| \frac{1 + \hat{\rho}_a}{1 - \hat{\rho}_a} \right|, \quad -\frac{2\hat{\rho}_a}{\pi} \arctan \left(\frac{1}{\hat{\rho}_a} \right), \quad -\frac{\hat{\rho}_a}{\pi} \log \left| \frac{1 + \hat{\rho}_a}{1 - \hat{\rho}_a} \right| + i\hat{\rho}_a$$

for $s < 0$, $0 < s < 4m_a^2$, and $4m_a^2 < s$, respectively, with $\hat{\rho}_a = \sqrt{|1 - 4m_a^2/s|}$ for all values of s , extending the expression of Eq. (1.2) into the regime below threshold. The more complicated expression for the case of different masses can be found, e.g., in Ref. [25].

If there is only a single resonance in a given channel, it is possible to feed the imaginary part of the Breit-Wigner function, Eq. (1.19) with an energy-dependent width, directly into a dispersion integral to get a resonance propagator with the correct analytic structure [29,30].

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1.3. Properties of resonances

A resonance is characterized not only by its complex pole position but also by its residues that quantify its couplings to the various channels and allow one to define a branching ratio also for broader resonances.

In the close vicinity of a pole the scattering matrix \mathcal{M} can be written as

$$\lim_{s \rightarrow s_R} \mathcal{M}_{ba} = -\frac{\mathcal{R}_{ba}^R}{s - s_R} , \quad (1.23)$$

where s_R denotes the pole position of the resonance R . The residues may be calculated via an integration along a closed contour around the pole using

$$\mathcal{R}_{ba}^R = \frac{i}{2\pi} \oint ds \mathcal{M}_{ba} .$$

In the baryon sector it is common to define the residue — in the listings called r_{ba} — with respect to the partial-wave amplitudes $a_{ba}(s)$ defined in Eq. (1.7) and with respect to \sqrt{s} instead of s . The two definitions are related via

$$r_{ba} = \sqrt{\frac{\rho_a(s_R) \rho_b(s_R)}{4s_R}} \mathcal{R}_{ba}^R . \quad (1.24)$$

For a single, narrow state with an energy-independent background in the resonance region, far away from all relevant thresholds one finds $\mathcal{R}_{ba}^R = \gamma_b(s_R) g_b g_a \gamma_a(s_R)$ with the real valued resonance couplings g_a defined in Eq. (1.11). Based on this observation one may use the straightforward generalization of Eq. (1.18) to define a partial width even for a broad resonance via

$$\Gamma_a^{R\text{res}} = \frac{|\mathcal{R}_{aa}^R|}{M_R} \rho_a(M_R^2) , \quad (1.25)$$

where $M_R = \text{Re}(\sqrt{s_R})$. This expression was used to define a two-photon width for the broad $f_0(500)$ (also called σ) [28]. Eq. (1.25) defines a partial decay width independent of the reaction used to extract the parameters. It maps smoothly onto the standard definitions for narrow resonances — cf. Eq. (1.17).

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